

# How to Light a

# Fire

## Studies of the sun's corona heat up

By RON COWEN

**Y**ou want hot? They've got hot. You want a puzzle? They've got a puzzle. For nearly 50 years, a simple fact about the sun's outer atmosphere, or corona, has bedeviled astronomers.

Though it lies several hundred thousand kilometers above the sun's surface, the corona has a temperature of at least 1 million kelvins, about 200 times greater than that of the surface itself. It's as if the air high above a candle were hotter than the flame that heats it.

Exactly how the sun has managed such a feat continues to confound astronomers. Because the corona is low-density, its high temperature results from a relatively small amount of energy. Just one ten-thousandth of the sun's total energy is sufficient to heat the corona, and scientists haven't lacked for theories about how this could happen. But no particular model has yet emerged as the winner because researchers haven't had the means to make the key observations required to thoroughly test predictions.

Enter the Solar and Heliospheric Observatory (SOHO), a spacecraft dedicated to studying the sun (SN: 5/4/96, p. 277). Launched last December, its findings have intrigued and even astonished solar astronomers. Recent SOHO measurements reveal that ionized atoms in some parts of the corona reach velocities greater than 200 kilometers per second. According to one model, these velocities correspond to thermal temperatures in excess of 100 million kelvins—nearly 100 times greater than had been previously recorded.

Faced with these blistering temperatures, solar astronomers would seem to have an even greater problem on their hands. But rather than stumping researchers, the SOHO observations may in fact point the way to a deeper understanding of the corona and the origin of its towering temperature.

*Ultraviolet image of a coronal hole near the sun's north pole, taken by SOHO's ultraviolet coronagraph spectrometer. The long, raylike structures are polar plumes. Coronal holes are regions of the sun's atmosphere from which the high-speed solar wind emerges; some ions in this area may have temperatures of up to 100 million kelvins.*



**V**isible to the eye only during an eclipse, when the moon slips between the sun and Earth, the corona stands out from the darkened sun like a pale wreath of light. This ghostly glow belies the fiery nature of the corona, a place where vast, arching magnetic fields hold sway and bursts of high-energy radiation stream into interplanetary space.

To study the corona, a spectrometer aboard SOHO recreates a solar eclipse by using an occulting disk, or coronagraph, to block the blinding light from the sun's surface. John L. Kohl of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Mass., and his colleagues, including Giancarlo Noci of the University of Florence, used the spectrometer to measure the wavelengths of ultraviolet light emitted by a variety of ionized atoms, ranging from hydrogen to magnesium.

The wavelength of light emitted by a single atom appears as a sharp spectral line. The spectrum of a group of atoms, however, spreads into a bell-shaped curve, because the speeds of individual atoms vary. Light radiated by atoms moving toward an observer gets shifted to shorter wavelengths, while light from atoms moving away gets shifted to longer wavelengths. The greater the range of velocities, the greater the smearing.

To Kohl's surprise, the ultraviolet spectral lines that his team measured in a particular part of the corona were extraordinarily broad, suggesting that the atoms there are extremely energetic and have high velocities.

In this case, the large velocities suggest that at a height of 500,000 kilometers above the

visible solar surface—well into the corona—hydrogen reaches a temperature of 6 million kelvins and oxygen an astounding 100 million kelvins. These numbers indicate that the atoms are heated roughly in proportion to their atomic weights, oxygen being 16 times more massive than hydrogen. Kohl and his colleagues reported the findings in June at a meeting of the American Astronomical Society in Madison, Wis.

**A**ssuming that the high speeds measured by Kohl's team do correspond to high thermal energies, two groups of researchers say they can explain the findings. They discussed their models at a SOHO workshop at Harvard in late June and at a biennial meeting on space physics that convened in July in Birmingham, England.

Both models begin beneath the corona with the generation of waves at the sun's

visible surface, or photosphere. Produced by the heat-driven motion of ionized gases that rise and fall within the solar cauldron, these waves represent oscillations constrained to move along the sun's magnetic field. Looping upward from the photosphere, magnetic field lines carry waves into the corona.

These waves have a certain set of frequencies. Charged particles in the corona also have characteristic frequencies, as they gyrate about the magnetic field lines.

If the frequency of a wave matches that of a gyrating particle, then something special happens. Under this resonance condition, the charged particles readily absorb the energy contained in the waves and rapidly accelerate to high velocities, which could account for Kohl's findings. Anyone who has pushed a child on a swing has observed the same type of phenomenon: When you push at the right time, in sync with the frequency at which the child is moving back and forth, the child will swing to great heights.

So far so good—except that the waves

er frequency vibrations that match the jiggle of charged particles in the corona.

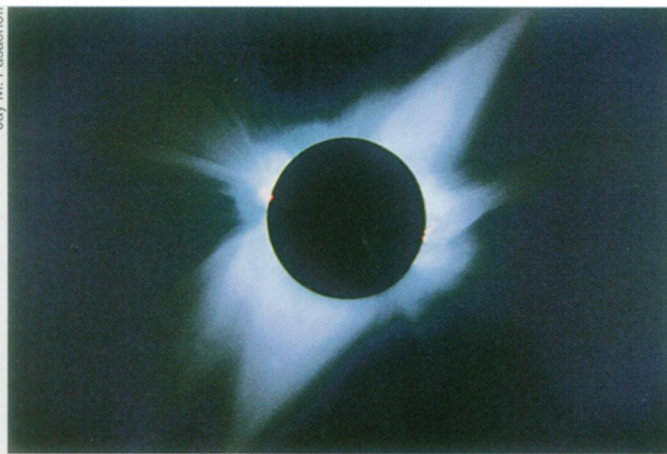
**W**hatever the mechanism behind the coronal heat, high-frequency waves may generate the high-speed solar wind that continually blows out from the sun and washes over the planets. This wind has its greatest speeds above the sun's poles (SN: 8/5/95, p. 89).

Robert Rosner of the University of Chicago notes that Kohl's measurements were made in regions known as coronal holes. In these regions, near the sun's poles, the magnetic field lines extend out into interplanetary space, providing the pathway for the sun's wind of charged particles to reach the planets.

By generating both coronal heat and solar wind, the high-frequency waves, Rosner says, would "kill two birds with one stone."

Rosner cautions that the SOHO findings may have another interpretation. The high speeds of charged particles measured by

the craft may not indicate that the particles have high thermal energies, which are created by random motion—atoms moving every which way. Rather, these velocities may be an indicator of coordinated atomic movement directed by low-frequency waves in the corona. Such waves can rev charged particles in the corona to speeds great enough to generate the high-speed solar wind, but they can't directly heat the sun's outer atmosphere. In that case, coronal heating might remain a puzzle, albeit a smaller one, since the corona would have a thermal temperature closer to 1 million kelvins than to 100 million kelvins.



*Solar eclipse of 1984, observed in visible light, unveils the pale glow of the corona.*

at the sun's surface are thought to have too low a frequency to match those of the gyrating charged particles. The two models part company in how they overcome this apparent obstacle.

Ian Axford and James McKenzie of the Max Planck Institute for Aeronomy in Katlenburg-Lindau, Germany, focus on minuscule flare-ups that have been observed near the base of the corona. They propose that these miniexplosions are caused by taut magnetic field lines that snap and reconnect, unleashing bursts of energy. These bursts could generate the requisite high-frequency waves needed to heat the corona.

In another model proposed several years ago, Joseph V. Hollweg of the University of New Hampshire in Durham and his colleagues came up with a different way to explain the high-frequency waves. In their scenario, the low-frequency waves encounter furious turbulence from the solar gases and convert to high-

**“K**ohl has enormously interesting results,” Rosner says. “If the measurements are a combination of temperature and velocity associated with wave motion, then he's discovered waves in the solar atmosphere. That's an absolutely wonderful coup.” Whether his observations solve a puzzle or simply change it, “He's in the catbird seat, and he has the pleasure of having theorists fight it out.”

A spacecraft currently on the drawing board might eventually settle the controversy, says Rosner. Known as Solar Probe, the proposed craft would take 3.5 years to reach the sun, venturing into the corona for about a day.

The probe “would stick its finger out and measure the temperature [of the corona] directly,” notes Rosner. With such a measurement, “the Solar Probe would eliminate all arguments.” □